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THE SURFACE AREA METHOD
AS USED IN THE DESIGN OF BITUMINOUS MIXTURES

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The procedure hereinafter described for fixing the oil content in graded aggregate mixtures has been generally referred to as the surface area method. It was developed from an original assumption that the optimum amount of liquid asphalt in a graded aggregate mixture should bear a definite relationship to the superficial surfaces to be covered. The problem involved first, means of estimating at least relatively the surface area of various gradings of aggregate, and second, knowledge as to the film thickness, or amount of asphalt required for a unit of surface.

In 1918, Capt. L. N. Edwards⁺, of Toronto, Canada, reported his work on portland cement concrete using surface area analysis as a basis for design. Edwards painstakingly counted the particles, estimated the volume and dimension of sand grains, and established surface area constants to represent the various sieve sizes. If these surface area values are plotted as ordinates against the reciprocals of the particle sizes as abscissa, the resulting straight line graph may be used for interpolation and extrapolation.

A difficulty arises, however, in establishing a constant to represent the surface area of materials passing the 200-mesh. At the time these surface area equivalents were adopted, little information was available as to the intimate gradation of fine dusts and fillers below the 200-mesh size. Partly due to lack of such information, and partly as a safeguard against over-oiling mixtures containing excess dust, the surface area constants used for materials passing the 200-mesh are unquestionably lower than the absolute values.

Having established a table of surface area equivalents, the study then involved a determination of the proper film thickness. It was first thought that this thickness might prove to be a constant, hence true for all materials regardless of grading. A little investigation proved that this was not the case, as it was soon evident that oil surfaces utilizing only fine materials, when analyzed, proved that a much thinner film was necessary than is the case in coarser gradings. Here seemed to be an explanation of previous unsatisfactory results with surface area methods. Engineering

⁺ Proceedings, A.S.T.M., Vol. XVIII, Part II, 1918.

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papers have expressed dissatisfaction with surface area formulas, it having been pointed out that a procedure found satisfactory for coarse mixtures invariably gave an excess of bitumen when applied to fine gradings such as sheet asphalt.

If an allowance is made for varying the film thickness (bitumen index) between fine and coarse gradings, it has not been found necessary to consider the voids in a mixture. A very pertinent article on this subject is "Variation in Asphalt Film Thickness on Mineral Aggregates" by Mr. A. R. Ebberts*. I might quote from Mr. Ebberts' article at this point.

"...We cannot completely fill the voids of an open mix with asphalt and still handle it on the job. In very fine mixes, we have an extremely narrow range of practical bitumen content. We are limited by small voids on the one hand and the necessity for adequate weather-proofing on the other. Asphalt is a lubricant and that property determines the maximum practical film thickness. Otherwise we sacrifice stability. Thus we must take into account both voids and areas in any system of design we adopt. Design based on areas must care for the voids by varying the bitumen index. Design based primarily on voidage may take care of areas by determining voids in a fluid medium that is absorbed in perhaps the same ratio as is asphalt."

So far as is known, this last procedure has not been worked out, and in the California laboratory we have found no occasion to concern ourselves with the void volume of bituminous mixtures. Porosity, which is more closely related to the size of the pores, is another story.

Having assigned surface area equivalents which represent a mathematical relationship between the surface areas of various gradings, it was further recognized that in their variety of shapes and surface texture, mineral aggregates present surfaces which may vary considerably from the theoretical sphere or cube usually employed in calculation. This deviation from the theoretical area might be cared for in two ways. The calculated surface area might be increased by an amount necessary to represent the additional surface area due to roughness and inequalities, or the adjustment might be made by increasing the film thickness, considering that rough particles will hold a thicker film of asphalt than

* Proceedings of the Sixth Annual Asphalt Paving Conference, 1927.

will smooth ones. This latter procedure was adopted, and the range from ordinary smoothest to roughest rock types was divided into ten divisions, which are referred to as surface factors, or "oil lines."

It might be well here to emphasize the point that the maximum safe amount of asphalt is that which the particles will carry without undue lubrication. It is not a question as to the amount which will stick to the rock surface. The upper limit of oil in any mixture is the amount which may be tolerated without producing instability. The lower limit is gauged by considerations such as raveling, susceptibility to water, deterioration with age, etc. The working range between these two extremes may be narrow or wide depending on the grading and the character of the aggregate.

Another point to emphasize is that the variation in bitumen index refers to the average particle size in a mixture, and does not mean that each individual particle holds a film of asphalt proportional to its diameter. So far as can be determined, by methods which are necessarily very inexact, there is little consistent difference between the thickness of films of asphalt on the large and small particles in a given mixture when the materials are thoroughly mixed. If there is any difference, the fine particles are as liable to have the heaviest coating, as it is well known that fine materials become coated sooner than do the large rocks in a mixture.

One of the difficulties in applying the surface area formula without first making trial mixes and stability tests is to determine the proper surface factor of "oil line" for a given aggregate. With experience, the oil line can be estimated very closely in many different types of aggregate. As a general guide it may be stated that a large majority of rock types can be properly oiled using oil line 3 or 4. This has proved to be the medium type. Quartz, chert and all hard glassy aggregates usually are amply oiled by using line 0. Crushed malapai or lava rock may require up to the 10 line, depending on the surface pits and inequalities. Fine particles commonly do not have the range in surface texture that is found in coarse material. Water-worn or wind-blown materials are invariably smooth.

In proportioning oil by weight, it is necessary to recognize the effect of specific gravity. The fundamental basis is, of course, to determine the volume of oil required for a volume of aggregate. If the aggregate is light in weight, the volume of a given weight will be greater, hence a greater volume of oil is needed. Paving asphalt weighs more than road oil, hence it requires a greater weight of asphalt to give the equivalent of volume.

If the aggregate is truly porous, so that oil soaks deeply into the rock particles, it is necessary to allow for such absorption in addition to the amount required by surface area analysis. In California's experience, such definitely porous aggregates are not common, and the only satisfactory method thus far has been one of trial, the aggregates being mixed with an assumed oil content, dried in an oven for a period, and then additional oil added until appearance or stability tests are satisfactory.

Following is a description of the method, including a table of surface area constants and curves for determination of film thickness. It is not assumed that these surface area constants are exact; and particularly in the case of any material finer than 200-mesh it would be impossible to assign any one constant to fit all aggregates.

In general, the method is based on analyzing the material by sieving, and calculating surface area values from the sieve analysis, with recognition of the following factors:

First, the optimum oil content is directly related to the surface capacity of the aggregate. This surface capacity is affected by three factors, each of which may vary independently of the others.

- (a) Most important is variation in surface area due to variation in grading. For the same weight, small particles have a greater surface area than large ones.
- (b) Variation in surface area due to shape and character of surface of particles.
- (c) Variation in absorption capacity of different aggregates.

Second, it has been established that the thickness of the oil film, or coverage factor, must be varied according to the average size of the particles.

The surface area equivalents for a sample of aggregate are calculated from the sieve analysis. The grading is first determined, and the amount of each size expressed as a percent of the total. (See Table III for example.) From the table of surface equivalents (Table II) constants are selected which represent the surface area in square feet per pound for the size groups. The percentage of each size is multiplied by the appropriate constant for that size, the summation of results giving a surface area equivalent for the grading represented by the entire sample. This method may be used in connection with any number of sieves. More accurate results are obtained with a large number of size divisions, particularly of the finer particles.

For comparison, see Table III, in which are shown three gradings, with surface areas in each case calculated with a complete set of sand screens, and also with only 4 sieves. It will be noted that gradings A and B show a considerable variation in surface area equivalents when computed from 4 measured sizes as compared to a computation using a full set of sieves. Grading C is a uniform grading which gives practically identical results regardless of whether a full set of sieves is used or not. The degree of error depends entirely on the particular grading concerned.

The results thus obtained represent a comparable mathematical relationship between surface areas of different aggregate gradings. Variation in surface area between different classes of material of same grading, due to difference in shape and surface characteristics of the particles must be estimated by inspection of the aggregate or determined by proper laboratory tests. Rough, irregular particles have, of course, a greater surface area than smooth, spherical ones. Variation due to absorption must be determined by trial or laboratory tests. This variation is due to the unequal capacity of different mineral aggregates to attract and hold asphaltic residues on their surfaces.

Having arrived at the surface area equivalent for a particular grading, the amount of oil required is calculated by multiplying the surface area by the bitumen index. The bitumen index is a variable factor indicating the amount of oil in pounds required to cover one square foot of surface area. The bitumen index chart (Figure 1) gives the coverage factor range which may be applied to different surface area equivalents. It will be noted that in fine grading combinations with high surface area, the coverage factor is smaller and the tolerances more restricted than in coarse combinations.

Corrections must be made for aggregates having a specific gravity above or below 2.65. The fundamental basis being, of course, relative volumes of oil and aggregate, it is obvious that a lighter aggregate will require more oil by weight and a heavier one will require less. The chart is arranged for fuel oil with a specific gravity of 0.98; if the oil or asphalt varies appreciably from this figure an allowance must be made. See formula on page 7.

The bitumen index curves are numbered from 0 to 10. These curves represent arbitrary surface factors designed to distinguish between particle surface textures with varying degrees of roughness. The lower curves apply to smooth, glassy particles, the highest curves to rock of the vesicular lava type. In application, the most appropriate curve is selected to represent the surface roughness of a given aggregate. The curve, then, becomes the only constant factor, and is the basis for laboratory recommendations to the field forces.

Any material represented by the lower surface factors is usually not highly stable. It is probably true that any aggregate or grading requiring a bitumen index below .0007 will be more likely to show distress in wet weather than will be the case where a thicker film is used.

There is reason to believe that this method is applicable to asphaltic concrete as well as to light oil mixes; and, furthermore, brief studies have indicated that required water cement ratios in portland cement concrete may be calculated from surface area analysis, provided that the principle of variable film thickness is recognized.

The form and application of this method rests on the following assumptions. Instability of a bituminous treated pavement and lubrication of the mass are synonymous terms. Then, since all road oils and asphalts are viscous liquids, the principles of lubrication are in operation, and it follows that small particles are more easily lubricated than large ones. There is a necessity for a diminishing oil coverage in order to maintain stability as the particles diminish in average size. (It should be understood that this is a design basis; all particles, large or small, in any given mixture have the same coverage factor or bitumen index.)

As applied in our laboratory in the preliminary investigation of aggregates, surface area equivalents are calculated from grading analysis as outlined. Trial mixtures are made with several oil contents calculated by means of surface factors arbitrarily selected from inspection of the aggregate. An attempt is made to select curves which will give an oil content both above and below the assumed optimum. Test specimens are formed from these mixtures and tested for stability in the Stabilometer. This test, being primarily a measure of internal friction of the mass, indicates the presence of excess oil by measuring the reduction in friction. From these test results, and consideration of local conditions, the surface factor or oil line is established and used as a basis for recommendation to the construction forces.

In fixing the amount of oil for a given aggregate and grading, it is with the general assumption that the most desirable oil content is the largest amount the aggregate will tolerate without developing instability. It is believed that all other considerations, such as resistance to moisture, raveling, impact, and oxidation are best met with a relatively high oil content. In the event of re-working, richer mixtures are preferable.

It should be clear, however, that the term "high" is used only in a relative manner. The highest permissible oil content may be indeed quite low in the percentage scale for some materials.

It is desired to stress the point that the series of curves shown in Figure 1 are not used merely to indicate a minimum or maximum range. Considerable effort is made to determine the precise surface factor which will provide the optimum oil content for a given aggregate. When once established, the particular surface factor becomes the only constant, and is the basis for our laboratory recommendations. The surface factor, or "oil line" furnishes a practical means of comparing the relative degree of a high oil content and a coarse grading requiring much less.

PROCEDURE

Having fixed the proper surface factor (oil line), and having computed the surface area equivalent from the grading of the aggregate in use (it should be understood that surface area equivalents should be calculated on the theoretical absolute volume grading rather than the apparent grading by weight), the following formula may be used:

$$R = \frac{2.65}{G_a} \times \frac{G_b}{.98} \times S_a B_1$$

R = Oil or Bitumen Ratio

G_a = Specific Gravity of Combined
Aggregate

G_b = Specific Gravity of Bitumen =

$$\frac{141.5}{131.5 + \text{A.P.I. Gravity}}$$

S_a = Surface Area Equivalent of Aggregate in Square Feet per Pound

B₁ = Bitumen Index as Determined from
Chart Figure 1. Surface Factor
from Laboratory Recommendation.

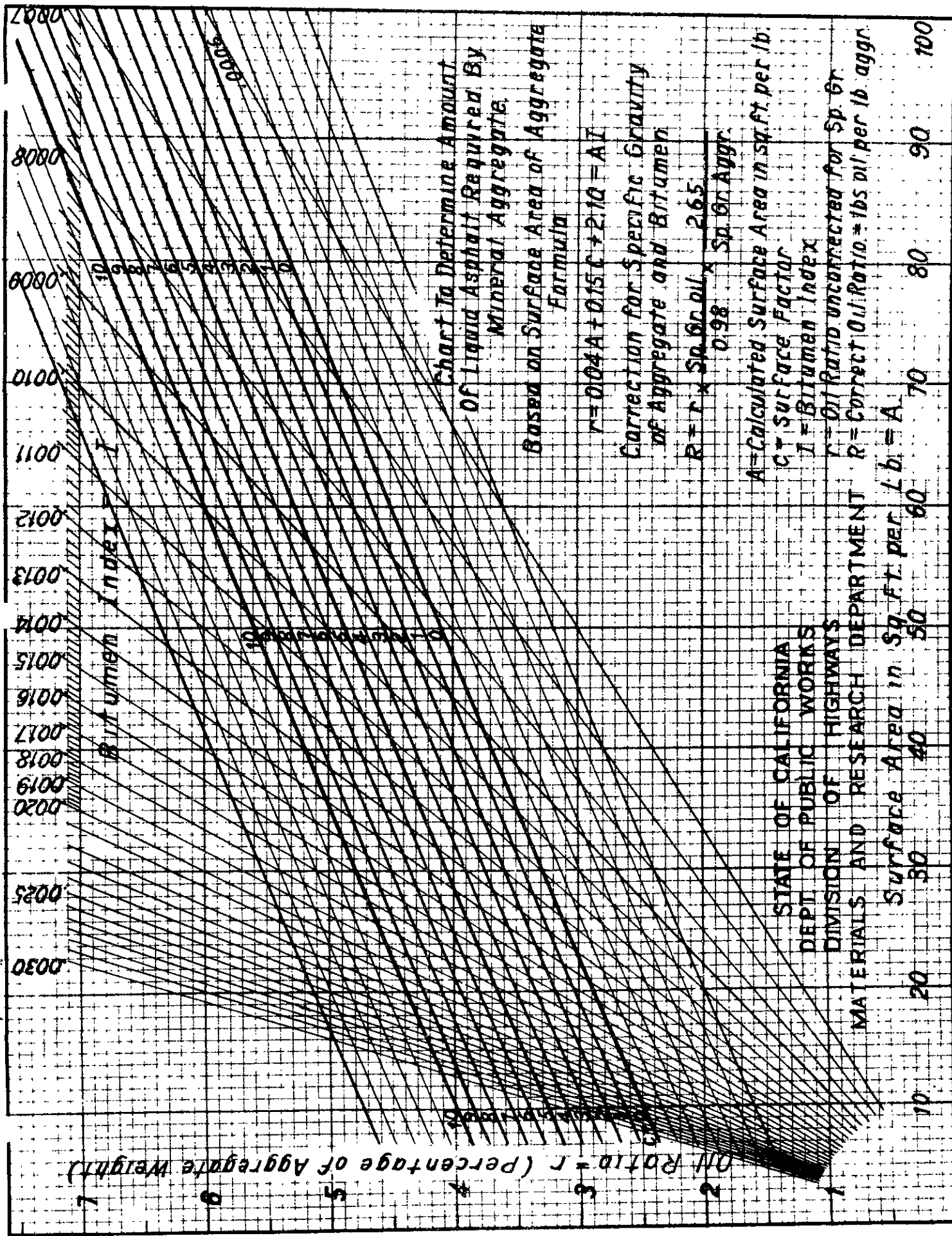
Assuming a sample grading as grading C (Table III) having a recommended surface factor #5 and with a specific gravity of 2.40.

Referring to the chart (Figure 1) it will be found that a surface area of 46.4 on curve number 5 gives a bitumen index of .00102 pounds (of oil per square foot). The product of surface area curves are based on a specific gravity of

2.65 and the sample has a specific gravity of 2.40, a correction will have to be made. Hence,

$$\frac{2.65}{2.40} \times \frac{.98}{.98} \times 46.4 \times .00102 =$$

.052 = oil ratio - - or, 100 lbs.
of aggregate will require 5.2 lbs.
of oil.



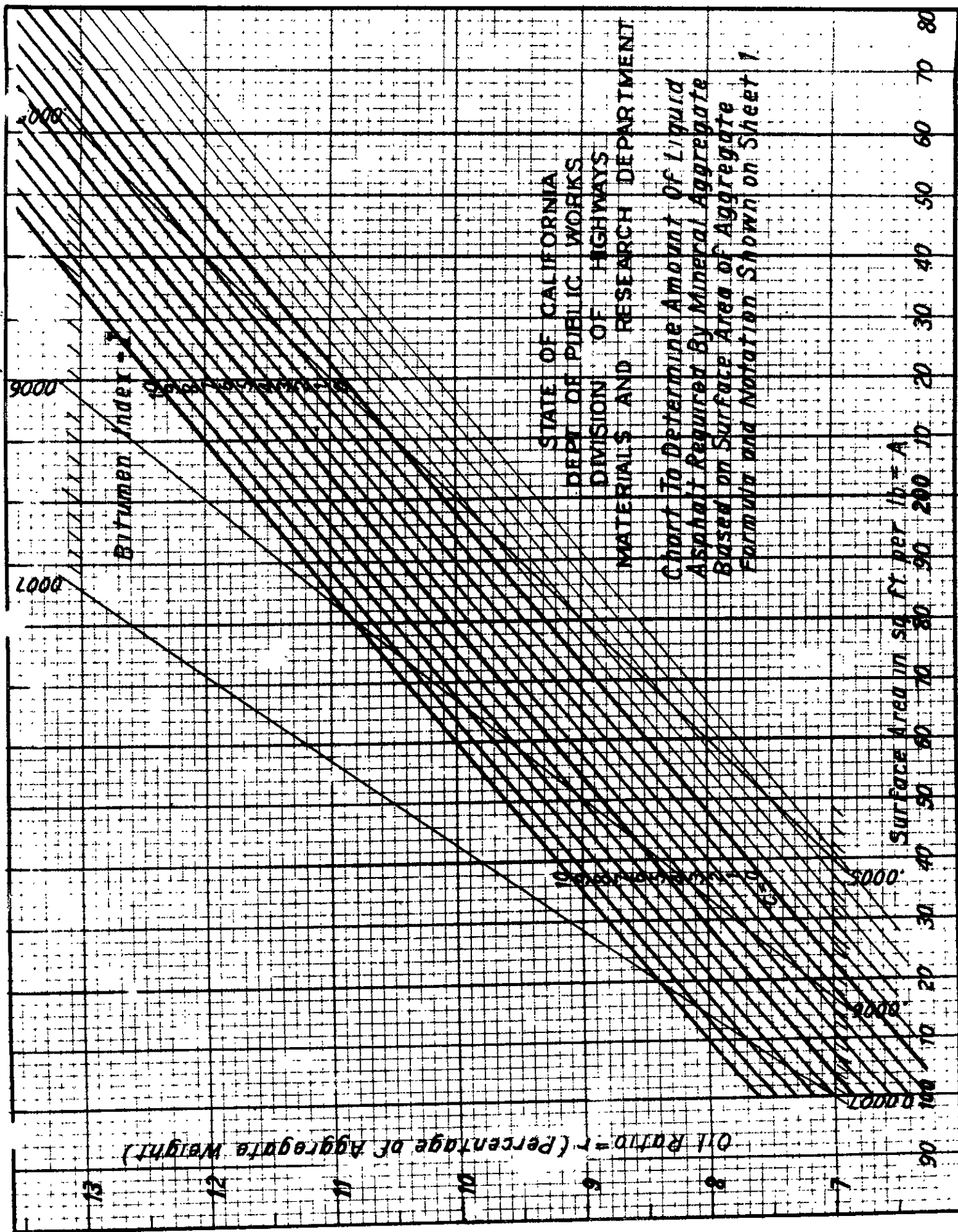


FIGURE I

CHART FOR DETERMINING OIL CONTENT FROM SURFACE AREA OF COMBINED AGGREGATE — AS COMPUTED FROM FIGURE I

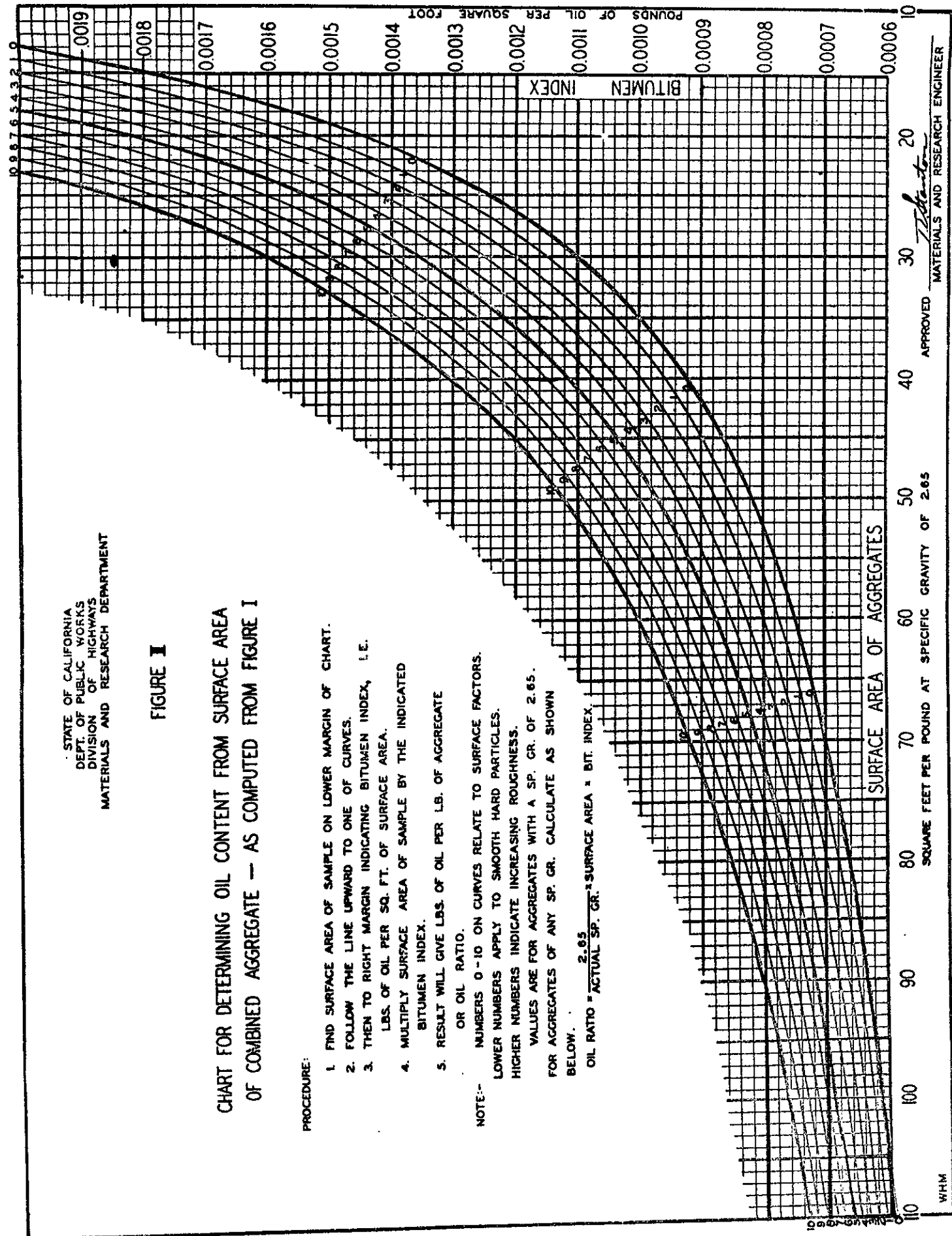
PROCEDURE:

1. FIND SURFACE AREA OF SAMPLE ON LOWER MARGIN OF CHART.
2. FOLLOW THE LINE UPWARD TO ONE OF CURVES.
3. THEN TO RIGHT MARGIN INDICATING BITUMEN INDEX, I.E.
LBS. OF OIL PER SQ. FT. OF SURFACE AREA.
4. MULTIPLY SURFACE AREA OF SAMPLE BY THE INDICATED
BITUMEN INDEX.
5. RESULT WILL GIVE LBS. OF OIL PER LB. OF AGGREGATE
OR OIL RATIO.

NOTE:-- NUMBERS 0-10 ON CURVES RELATE TO SURFACE FACTORS.
LOWER NUMBERS APPLY TO SMOOTH HARD PARTICLES.
HIGHER NUMBERS INDICATE INCREASING ROUGHNESS.

VALUES ARE FOR AGGREGATES WITH A SP. GR. OF 2.65.
FOR AGGREGATES OF ANY SP. GR. CALCULATE AS SHOWN
BELOW.

$$\text{OIL RATIO} = \frac{2.65}{\text{ACTUAL SP. GR.}} \times \text{SURFACE AREA} \times \text{BIT. INDEX}$$



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TABLE OF SURFACE AREA EQUIVALENTS

Table 1 10 Sieves			Table 2 7 Sieves			Table 3 6 Sieves			Table 4 4 Sieves			Table 5 4 Sieves			Table 6 3 Sieves		
Sieve No. Pass.	Ret.	Con- stant	Sieve No. Pass.	Ret.	Con- stant	Sieve No. Pass.	Ret.	Con- stant	Sieve No. Pass.	Ret.	Con- stant	Sieve No. Pass.	Ret.	Con- stant	Sieve No. Pass.	Ret.	Con- stant
270*		300															
200	270	200	200		260	200		260	200		260	200		260	200		260
100	200	120	100	200	120												
50	100	60				50	200	90	50	200	90						
30	50	30	30	100	46							30	200	72			
16	30	16				16	50	22									
8	16	8	8	30	12				8	50	17				8	200	45
4	8	4	4	8	4	4	16	6				4	30	9			
3/8	4	2	3/8	4	2	3/8	4	2	3/4	8	2	3/4	4	2	3/4	8	2
3/4	3/8	1	3/4	3/8	1	3/4	3/8	1	3/4	3/4	2	3/4	3/4	2	3/4	3/4	2

* Silt remaining in suspension and removed by elutriation.

Note: Value shown in Tables 2, 3, 4, 5, & 6 for passing #200 sieve applies to average dust. Will be in error for some materials.

APPLICATION: Use table according to number of test sieves used. Reducing number of sieves will reduce accuracy. By sieve analysis determine the amount of each size of aggregate. Express in terms of per cent of total. Multiply the per cent of each size by the constant given for that size. The constant is the equivalent area in sq. ft. of one pound of material of that size. Add results and total will represent surface area of the entire sample in terms of square feet per pound.

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REVISED TABLE OF SURFACE AREA CONSTANTS TO BE APPLIED
DIRECTLY TO SIEVE ANALYSIS EXPRESSED AS
CUMULATIVE PERCENTAGES PASSING EACH SIEVE

Table 1 10 Sieves		Table 2 7 Sieves		Table 3 6 Sieves		Table 4 4 Sieves		Table 5 4 Sieves		Table 6 3 Sieves	
Sieve No. Pass.	Con- stant	Sieve No. Pass.	Con- stant	Sieve No. Pass.	Con- stant	Sieve No. Pass.	Con- stant	Sieve No. Pass.	Con- stant	Sieve No. Pass.	Con- stant
270*	100										
200	80	200	140	200	170	200	170	200	188	200	215
100	60	100	74								
50	30			50	68	50	73				
30	14	30	34					30	63		
16	8			16	16						
8	4	8	8			8	15			8	43
4	2	4	2	4	4			4	7		
3/8	1	3/8	1	3/8	1						
3/4	1	3/4	1	3/4	1	3/4	2	3/4	2	3/4	2

*Silt remaining in suspension
and removed by elutriation.

Note: Value shown in Tables 2, 3, 4, 5,
and 6 for passing #200 sieve
applies to average dust. Will
be in error for some materials

APPLICATION: Use table according to number of test sieves used. Reducing number of sieves may reduce accuracy. By sieve analysis determine each size of aggregate. Express total amount passing each sieve in terms of per cent of total. (This is the normal procedure for recording combined gradings.) Multiply the percentage passing each sieve by the corresponding constant given in the table. The sum of these products will represent the surface area of the entire sample.

CAUTION: The constants from any one table must be used together and all of the constants must be used. For example, if Table 1 is used and the aggregate sample all passes a number 16 sieve, the constants for all sizes larger than the No. 16 even though not recorded in the grading analysis, must be multiplied by 1.00 and included in the sum.

TABLE III

SHOWING DIFFERENCES IN SURFACE AREA EQUIVALENTS CALCULATED FROM A SMALL NUMBER OF SCREEN SIZES AS COMPARED TO VALUES OBTAINED BY USING A FULL SET.

	STANDARD TESTING SIEVE	PERCENT PASSING	CONSTANTS FROM TABLE 1, FIG. II				CONSTANTS FROM TABLE 4, FIG. II												
			PROPORTION EACH SIZE	SURF. AREA	SURF. AREA		PROPORTION EACH SIZE	SURF. AREA	SURF. AREA										
			$\times \text{CONSTANTS} = \text{OF SAMPLE}$				$\times \text{CONSTANTS} = \text{OF SAMPLE}$												
GRADING 'A'	WASH	4	.04	\times	300	=	12.0	}	.12	\times	250	=	30.0						
	200	12	.08	\times	200	=	16.0		}	.19	\times	80	=	15.2					
	100	13	.01	\times	120	=	1.2												
	80	15	.02	\times	75	=	1.5												
	50	20	.05	\times	55	=	2.7												
	40	31	.11	\times	36	=	4.0	}	.14	\times	18	=	2.5						
	30	32	.01	\times	27	=	.3												
	20	34	.02	\times	18	=	.4	}	.55	\times	4	=	2.2						
	10	45	.11	\times	11	=	1.2												
	3	55	.10	\times	5	=	.5	}											
	1"	100	.45	\times	3	=	1.4												
				1.00				100											
SURFACE AREA OF SAMPLE IN SQ. FT. PER LB.							= 41.2	= 49.9											
CALCULATED OIL CONTENT USING O.O LINE FROM CHART, FIG. 10 = 3.7							= 4.1												
GRADING 'B'	WASH	9	.09	\times	300	=	27.0	}	.11	\times	250	=	27.5						
	200	11	.02	\times	200	=	4.0		}	.18	\times	80	=	14.4					
	100	23	.14	\times	120	=	16.8												
	80	26	.01	\times	75	=	.7												
	50	28	.02	\times	55	=	1.1												
	40	29	.01	\times	36	=	.4	}	.10	\times	18	=	1.8						
	30	36	.07	\times	27	=	1.9												
	20	37	.01	\times	18	=	.2	}	.61	\times	4	=	2.4						
	10	39	.02	\times	11	=	.2												
	3	63	.26	\times	5	=	1.3	}											
	1"	100	.35	\times	3	=	1.1												
				1.00				1.00											
SURFACE AREA OF SAMPLE IN SQ. FT. PER LB.							= 54.7	= 46.1											
CALCULATED OIL CONTENT USING O.O LINE FROM CHART, FIG. 10 = 4.3							= 3.9												
GRADING 'C'	WASH	6	.06	\times	300	=	18.0	}	.11	\times	250	=	27.5						
	200	11	.05	\times	200	=	10.0		}	.18	\times	80	=	14.4					
	100	18	.07	\times	120	=	8.4												
	80	20	.02	\times	75	=	1.5												
	50	25	.05	\times	55	=	2.7												
	40	29	.04	\times	36	=	1.4	}	.16	\times	18	=	2.9						
	30	32	.03	\times	27	=	0.8												
	20	36	.04	\times	18	=	0.7	}	.55	\times	4	=	2.2						
	10	45	.09	\times	11	=	1.0												
	3	60	.15	\times	5	=	0.7	}											
	1"	100	.40	\times	3	=	1.2												
				1.00				1.00											
SURFACE AREA OF SAMPLE IN SQ. FT. PER LB.							= 46.4	= 47.0											
CALCULATED OIL CONTENT USING O.O LINE FROM CHART, FIG. 10 = 3.9							= 3.9												